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Characterizing the urban heat island in current and future climates in New Jersey

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Abstract

Climate change caused by increased anthropogenic emissions of carbon dioxide (CO_2) and other greenhouse gases is a long-term climate hazard with the potential to alter the intensity, temporal pattern, and spatial extent of the urban heat island (UHI) in metropolitan regions. Particular meteorological conditions—including high temperature, low cloud cover, and low average wind speed—tend to intensify the heat island effect. Analyses of existing archived climate data for the vicinities of Newark and Camden, New Jersey indicate urban to suburban/rural temperature differences over the previous half-century. Surface temperatures derived from a Landsat thermal image for each site were also analyzed for spatial patterns of heat islands. Potential interactions between the UHI effect and projected changes in temperature, wind speed, and cloud cover are then examined under a range of climate change scenarios, encompassing different greenhouse gas emissions trajectories. The scenarios include those utilized in the Metropolitan East Coast Regional Assessment of Climate Variability and Change and the A2 and B2 scenarios of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES).

The UHI effect was detected in Newark and Camden in both satellite surface-temperature and meteorological station air-temperature records. The average difference in urban–nonurban minimum temperatures was 3.0 °C for the Newark area and 1.5 °C for Camden. Extrapolation of current trends and the selected global climate models (GCMs) project that temperatures in the case study areas will continue to warm in the current century, as they have over the past half-century. An initial analysis of global climate scenarios shows that wind speed may decline, and that cloud cover may increase in the coming decades. These generally small countervailing tendencies suggest that urban–nonurban temperature differences may be maintained under climate change.

Overall warmer conditions throughout the year may extend the spatial and temporal dimensions of the urban-suburban heat complex. The incidence of heat-related morbidity and mortality are likely to increase with interactions between the increased frequency and duration of heat waves and the UHI effect. Camden and Newark will likely be subjected to higher temperatures, and areas experiencing UHI-like conditions and temperature extremes will expand. Thus, urban heat island-related hazard potential is likely to increase in a warmer climate.

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1. Introduction

The process of urbanization can increase local temperatures in comparison to less built-up suburban/rural areas, creating an urban heat island (UHI). UHI conditions increase the risk of climatic and biophysical hazards in urban environments, including heat stress and heightened acute and chronic exposure to air pollutants. Climate change caused by increased anthropogenic emissions of carbon dioxide (CO_2) and other greenhouse gases is a long-term climate hazard with the potential to alter the intensity, temporal

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pattern, and spatial extent of the UHI in metropolitan regions.

This research considers the UHI in the past, present, and future by examining the dynamics of the UHI through both trend analysis and global climate change scenarios. The objective of this paper is to characterize the future interactions of the UHI and global climate change in urban areas. In a companion paper, *Mitigation of the Heat Island Effect in Urban New Jersey* (Solecki et al., 2005), we discuss UHI mitigation strategies, in particular the introduction of vegetation and reflective roofs, to reduce the UHI effect. Adoption of such strategies may become increasingly important as the climate warms.

2. Urban heat island as a hazard

The UHI effect refers to an increase in urban air temperatures as compared to surrounding suburban and rural temperatures (Oke, 1982; Quattrochi et al., 2000). Population shifts, urban and suburban growth, land-use change, and production and dispersal of anthropogenic emissions and pollutants interact with regional climate as well as with the frequency and intensity of specific weather events (Oke, 1973, 1982; Landsberg, 1981; Roth et al., 1989; Taha, 1997; Saaroni et al., 2000; Sailor, 1994). For example, the relation of urban vs. rural minimum temperature to decadal population change has been found to be pronounced and non-linear over time at the two urban Long-term Ecological Research (LTER) sites in Baltimore, MD and Phoenix, AR, while urban vs. rural maximum temperature data show no well-defined temporal trends (Brazel et al., 2000).

Heat islands develop in areas that contain a high percentage of non-reflective, water-resistant surfaces and a low percentage of vegetated and moisture-trapping surfaces. In particular, materials such as stone, concrete, and asphalt tend to trap heat at the surface (Landsberg, 1981; Oke, 1982; Quattrochi et al., 2000) and a lack of vegetation reduces heat lost due to evapotranspiration (Lougeay et al., 1996). Vegetation, especially in the presence of high moisture levels, plays a key role in the regulation of surface temperatures, even more than may non-reflective, or low-albedo surfaces (Goward et al., 1985).

The addition of anthropogenic heat and pollutants into the urban atmosphere further contributes to the intensity of the UHI effect (Taha, 1997). Urban centers tend to have higher energy demands than surrounding areas as a result of their high population density. Though the heat island effect reduces the need for heating in the winter, this is outweighed by the increased demand for air-conditioning during the summer months (Landsberg, 1981), which in turn causes increased local and regional air pollution through fossil-fuel burning electric power generation. The pollution created by emissions from power generation increases absorption of radiation in the boundary layer (Oke, 1982) and contributes to the creation of inversion layers. Inversion layers prevent rising air from cooling at the normal rate and slow the dispersion of pollutants produced in urban areas (Sahashi et al., 2004).

Many studies have investigated combinations of these influences for particular regions, focusing on statistical analyses of weather data considered over various spatial and temporal scales (e.g., Karl et al., 1988; Kidder and Essenwanger, 1995; Jauregui, 1997; Figuerola and Mazzeo, 1998; Klysik and Fortuniak, 1999; Morris et al., 2001; Gedzelman et al., 2003). To provide a better spatial characterization of urban–nonurban surface heating differences, some studies incorporate analyses of remotely sensed data, especially thermal imagery (e.g., Goward et al., 1985; Henry et al., 1989; Aniello et al., 1995; Lougeay et al., 1996; Roth et al., 1989; Quattrochi et al., 2000). However, surface-heating differences alone do not necessarily lead to a pronounced UHI effect. Particular meteorological conditions—including high temperatures, low cloud cover, and low average wind speeds—tend to intensify the effect (Kidder and Essenwager, 1995; Figuerola and Mazzeo, 1998; Morris et al., 2001; Arnfield, 2003).

UHIs are also associated with a range of acute and chronic health hazards, with acute heat stress the most obvious threat. High-profile killer heat waves, such as experienced recently in Chicago (1995) and France (2003), and UHIs are separate phenomena that, when occurring simultaneously, result in the potential for heightened numbers of deaths. Heat is a leading weather-related killer and the most sensitive areas are those with intense but irregular heat waves (Kalkstein and Smoyer, 1993). This includes cities like Newark and Camden, New Jersey, located in the Northeast United States.

Heat stress at an individual level occurs when a person facing heightened temperatures loses the ability to thermo-regulate, resulting in elevated body temperatures and physiological function breakdowns, failures, and in worst-case scenarios, death. Heat stress potential increases dramatically when daily high temperatures are elevated and when the diurnal temperatures range is reduced, such as during summers. These conditions also encourage a build-up of temperature-dependent secondary air pollutants. It is typical for heightened heat-related mortality to occur several days into a heat wave after several nights of elevated temperatures and associated physiological stress. This was the case for the Chicago heat wave (Klinenberg, 2002).

Heat waves are most threatening to traditionally vulnerable populations in urban centers—the very young, very old, poor, health-compromised (e.g., heart disease patients, people with HIV-AIDS) and disabled

(Kinney et al., 2001, pp. 103–147). The poor are vulnerable because they might lack air conditioning, which can be used to mitigate the indoor temperature threat, or they might live in housing that lacks proper insulation or air circulation. In general, individuals living on top floors are more at risk because of higher indoor temperatures on these floors. Specifically, individuals living in top-floor apartments of older, poor air-circulation buildings with black, tar roofs typically experience the highest summer temperatures. Individuals who maintain two or more of any of these indicators are at highest risk of heat stress: the largest proportion of deaths in Chicago 1995 was by poor elderly residents living in top floor apartments without adequate ventilation or air conditioning (Klinenberg, 2002).

The UHI and associated heightened temperatures are related to heightened secondary air pollution concentrations and resulting acute and chronic exposure impacts. These include a range of respiratory problems including acute asthmatic attacks requiring hospitalization. Heat islands are especially a problem in urban areas that already have difficulty meeting federal air pollution standards. For example, in recent years, the case study site of Newark has been unable to achieve compliance with ozone standards set by the Environmental Protection Agency (US EPA Office of Air Quality Planning and Standards, 2001), contributing to increased incidences of reduced lung function and asthma related to ozone exposure (American Lung Association, 1997; Kinney et al., 2001).

In the future, the hazard potential of the UHI may be enhanced due to climate change. The globally averaged near-surface air temperature is projected to increase by 1.4–5.8 °C over the period 1990–2100, given a range of greenhouse gas emissions and climate sensitivities to changes in radiative forcing (IPCC, 2001). Especially important are shifts in minimum average temperature, cloud cover and wind speed. Climate change has the potential to significantly alter the intensity (e.g., size and duration) and increase the spatial extent of heat islands in urban environments. As temperature warms, the frequency with which UHI conditions occur could grow. Researchers already have predicted that the duration of heat waves are projected to increase in the future (e.g., Rosenzweig and Solecki, 2001).

Interactions between the UHI effect and heat waves are likely to lead to increased incidences of morbidity and mortality related to heat stress, particularly in mid-latitude cities that experience infrequent, but extreme heat waves (Kalkstein, 1995). Since current meteorological conditions associated with heat island intensification are also associated with intense pollution episodes in cities (NRC, 1991), higher temperatures and changes in cloud cover in the future could lead to higher rates of smog formation, and lower wind speeds may tend to keep pollutants concentrated over urban areas, with associated health effects. Integrated modeling of the effect of climate change on ozone concentrations and health effects in the New York Metropolitan region has shown that climate change could cause a 4.5% increase in the number of summer ozone-related deaths by the 2050s (Knowlton et al., 2004). Furthermore, increases in ozone mortality in the 2050s may spread beyond the urban core into less densely populated suburban areas in New Jersey (Knowlton et al., 2004).

3. Urban heat island analysis

3.1. Case study sites

We examine the UHI of two cities (Newark and Camden) and their immediate environs in the state of New Jersey. New Jersey is on the Mid-Atlantic coast of the US and is located in a temperate, mid-latitude climate zone. Westerly winds are the dominant climatic feature, but easterlies, and particularly southeasterlies off the Atlantic Ocean and Delaware Bay moderate the temperature (Ludlum, 1983). Newark is located at sea level near the eastern edge of the state's central climate zone. The city, which occupies 62 km^2 and has a population density of 4461 people per square kilometer (US Census, 1996), is bounded by densely populated urban and suburban areas to the north, south and west, and the Passaic River and Newark Bay to the east (with New York City located approximately 10 km to the east). Because Newark is located in a shallow topographic bowl, the city's western sprawling suburbs are at higher elevations (up to 180 m) than the city itself. Numerous steel office buildings rise ten stories and higher in Newark's commercial downtown area. In residential districts and lesser commercial areas, structures are generally two or three stories high and are brick, concrete block, or wood frame.

Camden, located in the southwestern portion of the state on the eastern side of the Delaware River, is a small urban area within the Philadelphia Metropolitan Region. It is surrounded by dense suburban areas, with rural areas located further to the southeast and east. Camden occupies 29.3 km^2, and has a population density of nearly 3000 people per square mile (US Census, 2000). The city has a smaller downtown area than Newark, with most buildings rising five-to-seven stories. Residential and neighborhood commercial areas are similar in structure and material to Newark. Camden's position near the Atlantic Coast and Delaware Bay makes the city more susceptible to wind influences than the urban and suburban areas of Philadelphia further west.

Both Camden and Newark are old industrial centers, with many stationary pollution sources (e.g., nitrogen dioxide emissions sites) located within their borders and immediate surrounding communities (US EPA Office of Air Quality Planning and Standards, 2001). Emissions of volatile organic compounds are also concentrated in and around these urban areas. Both cities are criss-crossed by major transportation corridors that add to their pollution load. Newark Liberty International Airport, one of the busiest airports in the United States and a major source of atmospheric pollution, is located on the southern edge of the downtown area (NRDC, 1996). The Philadelphia International Airport is located 10 km southwest of Camden.

The populations of both cities are predominantly low-to-moderate income, minority, and increasing immigrant. Camden has the highest proportion of low-income residents of any city in the state (35.5% live below the poverty level—US Census 2001); while Newark's situation is only somewhat better (28.4% live below the poverty level—US Census 2001). Both cities, but particularly Newark, have a relatively high percentage of older and younger residents, and residents whose primary language is not English.

Overall, these populations are particularly vulnerable to the health effects associated with the UHI and exposure to atmospheric pollution. During the first of three heat waves in New York City in July, 1999, 33 people died of heat-related causes (Rosenzweig and Solecki, 2001). Nearby cities such as Newark and Camden that already experience higher temperatures and, in particular, higher minimum temperatures, are likely to be particularly sensitive to intensifying heat waves under climate change.

4. Methods

We use thermal satellite imagery and meteorological station data to characterize the UHI effect at the two study sites. Urban–nonurban surface-heating differences were calculated from Landsat thematic mapper (TM) remotely sensed thermal satellite imagery. Both are mid-morning summer images; the Newark image was acquired on 2 June 1996 and the Camden image was acquired on 14 August 2002.[1]

The existence and magnitude of urban–nonurban air temperature differences were documented using monthly maximum, minimum and mean temperature data for the period 1950–1999 from the National Climatic Data Center (NCDC).[2] Urban–nonurban differences in minimum temperature serve as the primary indicator of the magnitude of the heat island effect because urban–nonurban temperature differences are normally most pronounced at night. At Newark, the effect of wind speed and cloud cover on UHI intensity was examined at a monthly scale over the period 1984–1995 to determine the strength of the correlation in the study region. Wind speed, daytime sky cover, and overall sky cover data for Newark airport were used. Daytime sky cover is the percentage of the sky covered with clouds between sunrise and sunset. Overall sky cover is the percentage of sky covered with clouds over 24-h periods measured from midnight to midnight. The selected meteorological stations, their locations, and their land-use classifications are shown in Fig. 1 and Table 1. Urban stations were defined as those stations located in areas with more than 2000 people per square kilometer. Trends in temperature and UHI intensity over the last half-century were then examined.

Potential interactions between the UHI effect and projected changes in temperature, wind speed, and cloud cover were considered using a range of climate change scenarios. The scenarios were developed from extrapolation of current trends and global climate models (GCMs), following the Metropolitan East Coast Regional Assessment of Climate Variability and Change (Rosenzweig and Solecki, 2001) and the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (IPCC SRES, 2001). Projected climate variables include regional minimum, maximum and mean temperature, as well as wind speed

[1]Images were calibrated to known solar zenith angles and surface temperatures were derived from reflectance in Band 6 (10.40–12.50 μm). Although the remotely sensed data are specific to particular points in time, it has been shown that surface heating patterns tend to remain the same throughout the day, though the magnitude varies (Brazel et al., 1993). Since most surface features have emissivities close to unity, remotely sensed radiative temperatures are generally good indicators of true surface temperatures (Goward et al., 1985).

The 6-year gap between the 1996 Newark image and the 2002 Camden image may affect direct comparisons between the two study regions because urban land-use may have changed in the interim. However, the magnitude of such an effect is likely to be small compared to the magnitude of underlying regional differences.

[2]Stations with near-complete data records were chosen for this portion of the analysis. If one month of data was missing for a station in any particular year, then that month was excluded from the averages taken for all three stations and the mean value was used in the calculation. If more than 1 month of data was missing for any station in any particular year, then that year was excluded from the data set. A correction for differing elevations at station locations was made using the average environmental lapse rate, especially necessary for the weather stations in the Newark case study. The Newark Liberty International Airport station, located on the southern edge of the city, was selected as a proxy for the urban center of Newark and the Philadelphia International Airport station, located 10 km southwest of Camden, was selected as the urban center proxy for Camden. Neither city had a meteorological station located within the city center. In the case of Newark, the airport is within the urban area, so meteorological conditions at the airport are likely to be more representative of the urban center than Philadelphia airport is of Camden. However, in the absence of better alternatives—i.e. other meteorological stations—and given that Camden and Philadelphia are both hot spots within the same heat island archipelago, using Philadelphia Airport as the Camden proxy was determined to be the best option.

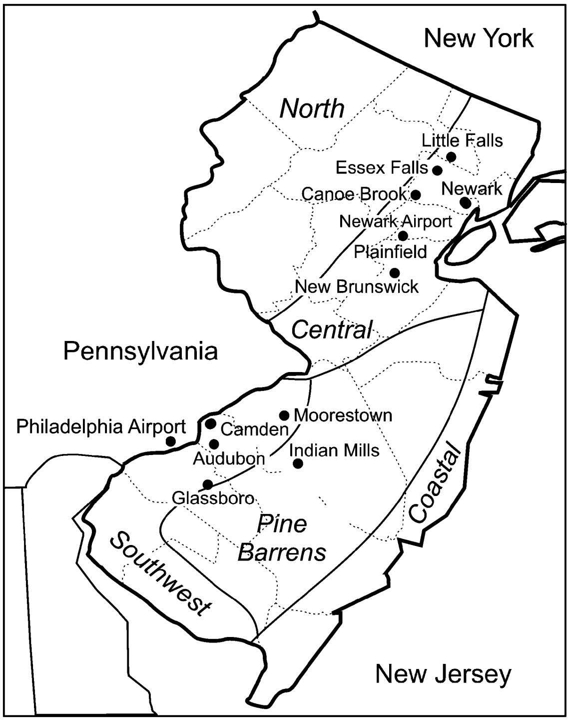

Fig. 1. New Jersey climate zones and locations of meteorological monitoring stations.

and cloud cover for the 21st century (Table 2). The current trends scenarios were developed by combining the data from the meteorological monitoring stations surrounding Newark and Camden.[3]

The three GCMS are: The Goddard Institute for Space Studies (GISS) atmosphere–ocean coupled model (Russell et al., 1995), the Canadian Centre for Climate Modeling and Analysis (CC) atmosphere–ocean coupled model (Flato et al., 1997), and the Hadley Centre (HC) atmosphere–ocean model (Johns et al., 1997). The simulations with the CC and HC GCMs are based on IPCC greenhouse gas emission scenarios for the 21st century (1% per year increase of equivalent CO_2 concentrations in the atmosphere) (IPCC, 1996). The GISS GCM scenarios (GS) use observed GHGs until 1990 and compounded 0.5% annual increases in GHGs thereafter. Sulfate aerosols are emitted as by-products of industrial activities and create a cooling effect as they reflect and scatter solar radiation. The scenarios that incorporate both greenhouse gases and sulfate aerosols (GS) tend to be slightly cooler than those with greenhouse-gas (GG) forcing alone. GCM projections were linearly interpolated across grid boxes to the latitude and longitude of Newark and Camden.

We also tested the effects of two further GISS GCM simulations based on the IPCC Special Report on Emissions Scenarios (SRES) A2 and B2 scenarios (IPCC, 2000). The A2 scenario can be generally described as a pessimistic future. It describes a world with high population growth, relatively slow economic growth and technological change. A2 CO_2 emissions are high. The B2 scenario may be described as a more optimistic future. Population growth is intermediate, as is economic growth. Technological change is relatively slow. However, in the B2 scenario CO_2 emissions are steadily reduced throughout this century, resulting in lower levels of climate forcing. GISS GCM simulations forced with the resulting SRES A2 and B2 greenhouse emissions were analyzed for future temperature, wind speed, and cloud cover.[4]

[3]Any station for which a significant amount of data was missing or that was not operational for more than three consecutive years over the 50-year period was not included. If more than 1 month of data was missing from any year, then that station's data was discarded from the yearly average. The current trends scenarios are a linear projection of historical trends over the last half-century and do not assume any additional climate forcing from greenhouse gases or sulfate aerosols. The half-century time period was chosen because a larger number of stations had complete data for this time period than one beginning in 1900. Also, climate forcings and regional responses may be more strongly linked in the latter part of the 20th century (IPCC, 2001).

[4]Projections made by GCMs are reflections of the current state of knowledge of the processes in the climate system, but still contain uncertainties. Because the projections are made for large areas, they do not resolve local and even regional-scale intricacies in the climate system, especially when these are related to urban microclimate modification. Nevertheless, the models do provide a generalized regional representation of possible future climates.

To obtain a fuller characterization of climate trends, we need to separate trends related to local changes in land use, population (both growth and distribution), and local release of pollutants including heat, moisture, greenhouse gases, and ozone precursors, from regional climate trends influenced by changes in ocean–atmosphere heat and moisture exchange that may give rise to changes in synoptic-scale weather, temperature, and wind patterns. For example, Kalkstein et al. (1998) analyzed recent trends in synoptic air masses in US cities for the period 1948–1993 and found that Newark has statistically significant changes in both minimum temperature (0.33 °C/decade) and maximum temperature (0.16 °C/decade) for the moist tropical (MT) air masses during summer. Synoptic differentiation permits more detailed evaluation of trends than simple time-series of meteorological variables. Such detailed analyses of meteorological data over longer time periods, and especially of wind speed and cloud cover data are needed to extract a more complete understanding of the current and future heat island effects of both Newark and Camden.

Another method is to utilize regional mesoscale climate models (RCMs) with greater spatial resolution than the GCMs used in this study to provide a more detailed description of how the current UHIs functions and how the intensity of the UHI effect may interact with climate projections for the 21st century. The use of improved calculations of the energy exchange in complex urban areas in RCMs would also contribute to better simulation of the current and future UHI in Newark and Camden (e.g., Grimmond and Oke, 2002; Masson et al., 2002; Offerle et al., 2003).

Table 1
Site characteristics of meteorological monitoring stations

Station	Lat. (dec °)	Long. (dec °)	Elev. (m)	Dist. from proxy (km)	Land-use	Use of station data
Newark region						
Newark Airport (Newark proxy)	40.72	−74.18	3	0	Urban	Urban heat island Current trends scenario
Canoe Brook	40.75	−74.35	55	15.9	Suburban	Urban heat island Current trends scenario
Essex Fells	40.83	−74.28	107	16.3	Suburban	Urban heat island Current trends scenario
Little Falls	40.88	−74.23	46	19.8	Suburban	Urban heat island Current trends scenario
New Brunswick	40.47	−74.43	26	30.3	Urban	Current trends scenario
Plainfield	40.60	−74.40	27	23.6	Urban	Current trends scenario
Camden region						
Philadelphia Airport (Camden proxy)	39.87	−75.23	2	0	Urban	Urban heat island Current trends scenario
Audubon	39.88	−75.08	12	12.9	Suburban	Urban heat island Current trends scenario
Glassboro	39.73	−75.10	31	18.7	Suburban	Urban heat island Current trends scenario
Indian Mills	39.80	−74.78	31	38.8	Rural	Urban heat island Current trends scenario
Moorestown	39.97	−74.83	14	24.6	Semi-rural	Urban heat island Current trends scenario

5. Results and discussion

5.1. Urban–nonurban surface heating differences

In both Newark and Camden, surface temperatures within the city proper were higher than surface temperatures in suburban and rural areas as recorded by Landsat TM (Fig. 2). Higher surface temperatures during the day indicate the potential for elevated evening and night-time air temperatures in these two cities, as energy stored by urban surfaces warms the air through conduction and convection. In Newark, surface temperatures were on-average 5.9 °C higher in the downtown area than in the suburbs. Surface temperatures across the Newark region ranged from 22.2 to 38.3 °C, though the fraction of pixels with temperatures greater than 31.5 °C was less than 1%. In the Camden image, heavily wooded surfaces southeast and east of the city were approximately 20 °C cooler than the urban surface areas, which can exceed 40 °C in the hottest areas of Camden and Philadelphia. Within both Newark and Camden, there was a great degree of variability between neighborhoods. The more built-up neighborhoods consistently had higher surface temperatures (about 7–9 °C more) than the lower density, more vegetated areas of the cities.[5]

[5]Neighborhoods in the Ironbound section of Newark (north of the Airport and south of the Passaic River) contained the highest surface temperatures, with surface temperatures ranging from 26.4 to 33.2 °C. In the high-rise business district, values were slightly lower, reaching a maximum of 32.7 °C. In the Forest Hills section of the city (north of the business district, east of Branch Brook Park), temperatures were found to be far lower than in other sections of the city, ranging from 20.7 to 29.8 °C. This section has detached housing and more vegetation than other areas of the city. In central Camden, which has the highest density of buildings and non-vegetated vacant blocks (after asphalted), surface temperatures were highest. The thin irregular ribbon of cooler temperatures through Camden is a landscaped interstate highway corridor (I-676) crossing the city north to south. Hot strips are developed commercial or industrial areas with relatively little vegetation and extensive thermal mass from the paved surfaces and buildings. Suburban areas surrounding Camden are 5–15 °C cooler than the city.

5.2. Urban–nonurban air temperature differences and trends

In each of the 50 years included in the meteorological dataset, average annual urban temperatures were higher than suburban/rural temperatures, except in the case of Audubon, just outside of Camden (Fig. 3). In the Newark area, the average annual difference in mean temperature was 1.6 °C and the average annual difference in minimum temperature, taken as the indicator of the average intensity of the UHI effect, was 3.0 °C.

Mean and minimum air temperature differences for the Camden area tended to be less pronounced, averaging 0.3 °C for mean temperature and 1.0 °C for minimum temperature. The lower UHI magnitude for Camden is likely at least partially explained by Camden's smaller size and lower average building height as well as by differing geographic and climatic features.

Table 2
Descriptions of climate change scenarios

Scenario	Description	Grid box	Variable(s)
Current trends	Projection of historical temperature trends (1950–1999) based on data from meteorological stations in the Newark and Camden regions. No additional forcing from greenhouse gas (GHG) emissions.	n/a	Temperature
HCGG	Hadley Center, with forcing from GHGs. 1% equivalent CO_2 increase per year before present and 1% compounded increase per year in the future.	2.5° lat. 3.75° long.	Temperature
HCGS	Hadley Center, with forcing from GHGs and sulfate aerosols. 1% equivalent CO_2 increase per year before present and 1% compounded increase per year in the future.	2.5° lat. 3.75° long.	Temperature
CCGG	Canadian Center with forcing from GHGs. 1% equivalent CO_2 increase per year before present and 1% compounded increase per year in the future.	3.75° lat. 3.75° long.	Temperature
CCGS	Canadian Center with forcing from GHGs and sulfate aerosols. 1% equivalent CO_2 increase per year before present and 1% compounded increase per year in the future.	3.75° lat. 3.75° long.	Temperature
GSGG	Goddard Institute for Space Studies, with forcing from GHGs. Observed GHGs until 1990 and compounded 0.5% increases thereafter. GSGG is an ensemble of two members with different initial conditions.	4.0° lat. 5.0° long.	Temperature Wind speed Cloud cover
GSGS	Goddard Institute for Space Studies, with forcing from GHGs and sulfate aerosols. Observed GHGs until 1990 and compounded 0.5% increases thereafter. GSGS is an ensemble of two members with different initial conditions.	4.0° lat. 5.0° long.	Temperature Wind speed Cloud cover
SRES A2	Goddard Institute for Space Studies, with increased rates of GHG emissions based on a continuation of current development and land-use trends.	4.0° lat. 5.0° long.	Temperature Wind speed Cloud cover
SRES B2	Goddard Institute for Space Studies, with GHG emissions steadily reduced over the course of the century due to changing development and land-use practices.	4.0° lat. 5.0° long.	Temperature Wind speed Cloud cover

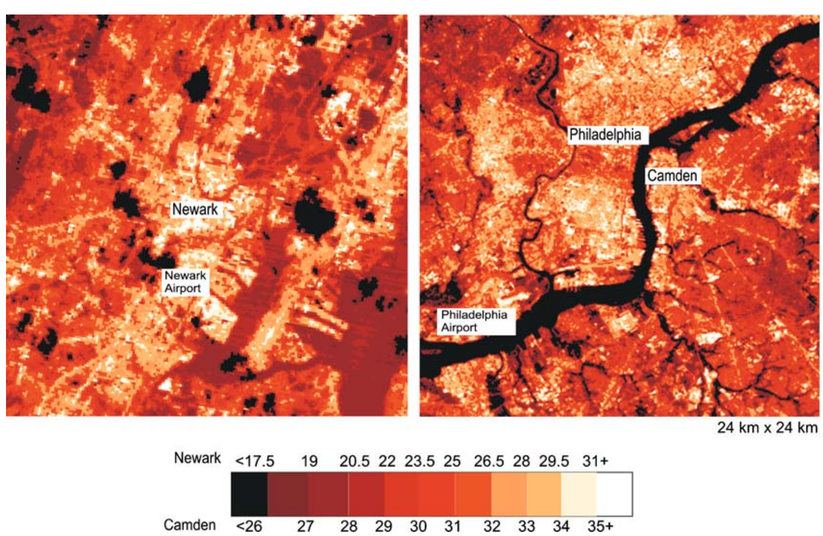

Fig. 2. Thermal images (a) Newark, (b) Camden.

In contrast, Newark's combination of higher elevations and greater precipitation in the suburbs as compared to the city proper may amplify the magnitude of the air temperature differences there. The inclusion of Audubon as a nonurban station also dampened the urban–nonurban temperature difference for Camden. Removing Audubon, the average magnitude of minimum temperature differences in Camden is 1.5 °C.

Another major consideration in Camden is the use of the Philadelphia Airport station as a proxy for Camden proper (see footnote 3). Camden and Philadelphia are both part of the same urban complex. As is clear from the satellite images, heat islands should not be thought of as urban cores surrounded by concentric circles with decreasing temperatures as the circles expand outward. Rather, heat islands can be more accurately described as

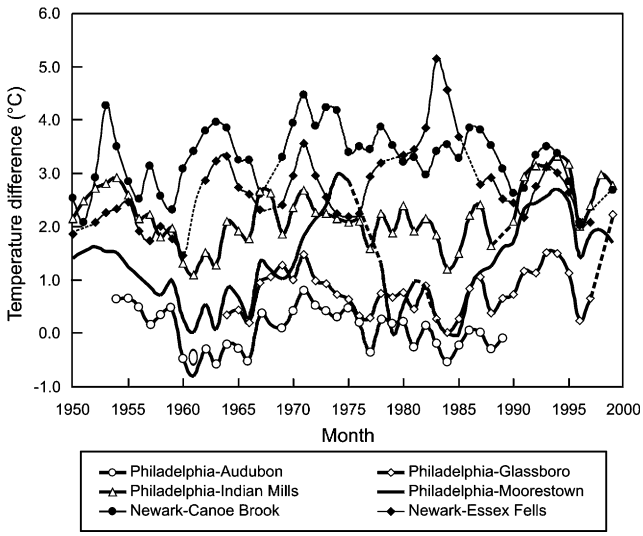

Fig. 3. Average annual differences in urban–nonurban minimum temperature.

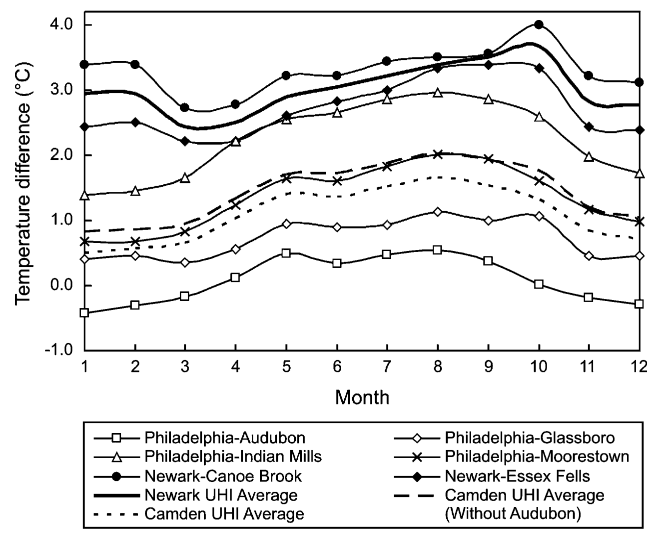

Fig. 4. Average monthly differences in urban–nonurban minimum temperature.

archipelagos, within which hot spots are unevenly distributed. Both Camden and Philadelphia are such hot spots within the Philadelphia Metropolitan Region. Given the lack of meteorological data for Camden, Philadelphia Airport is probably the best available proxy; however, the airport's location 10 km to the south west of Camden and on the other side of the Delaware River, certainly introduces error into the calculations. Given that the Audobon station, which is the closest station to Camden proper, had daytime temperatures consistently higher than Philadelphia Airport, it is likely that the Camden heat island is under-estimated (i.e. that Camden's temperatures daytime temperatures are higher than Philadelphia Airport's daytime temperatures). Further work is needed to determine the role of each part of the archipelago in the overall heat island dynamics.

In general, urban–nonurban differences in minimum air temperature at both case-study locations are within the range of differences derived at other geographic locations using similar methods (Sailor, 1994; Figuerola and Mazzeo, 1998; Klysik and Fortuniak, 1999; Saaroni et al., 2000; Morris et al., 2001). The observations are also in general agreement with the results of a study completed in the Newark metropolitan area in 1976 (Zois and Sandoval, 1985). The Zois and Sandoval study collected temperature data by taking automobile transects at night, rather than using observations collected at meteorological monitoring stations. The results indicated that the UHI effect in the region at that time ranged in intensity between 1.1 and 8.8 °C, with variation in magnitude strongly dependent on wind speed (Zois and Sandoval, 1985).

5.2.1. *Monthly differences*

The temperature records are characterized by both interannual and monthly variability. In Camden, the magnitude of the UHI effect is greatest in August; in Newark, the effect is maximized in October (Fig. 4). There are several factors that contribute to inter-seasonal variance in UHI intensity, including differences in sun angle, synoptic-scale weather, vegetative cover, and amount of anthropogenic heat and pollutants released into the urban environment. The latter may contribute both to small-scale warming effects and to enhanced solar blocking from aerosol-enhanced clouds that results in cooling. Surface temperatures tend to peak several months following the early summer insolation maximum due to the build up of thermal inertia. This may explain the peak in UHI magnitude seen in the Newark region in October. Camden's heat island is most pronounced in late summer, rather than mid-autumn. In Camden, lower evapotranspiration in late summer combined with the build-up of thermal inertia may contribute to the heat island maximum in August. Evapotranspiration tends to peak with the maximum solar radiation in early summer, but trails off later in the summer (Henderson-Sellers and Robinson, 1986).

The monthly variability in Newark's heat island intensity can be at least partially explained by monthly differences in wind speed and cloud cover (Fig. 5). In October, the average intensity of the UHI effect is maximized at 3.9 °C; this is the same month during which both daytime and overall sky cover are minimized (56% and 62%, respectively, compared to average values of 60% and 64%). However, though there appears to be a strong linear association between cloud cover and UHI intensity, the correlation is based on

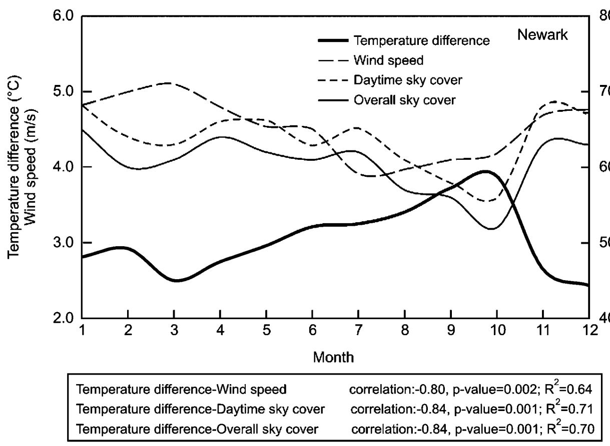

Fig. 5. Average monthly urban–nonurban temperature difference, wind speed, daytime sky cover, and night-time sky cover at Newark.

differences in averaged data that are less than 10%, and the original cloud cover data are correct only to the nearest 10% (NCDC, 2000). Winds speeds during October are also lower than average—4.2 m/s as compared to an average of 4.5 m/s, though wind speeds are lowest in July at 3.9 m/s. Taken together, wind speed and cloud cover appear to explain much of the monthly variation in urban–nonurban temperature differences. However, it may be that on the actual days on which wind speed and cloud cover are low are not the actual days on which the UHI effect is maximized. Analysis of daily temperature, wind speed, and sky cover data is needed to corroborate this result.

5.2.2. Trends in UHI

The 50-year trends in urban–nonurban mean and minimum temperature differences were not significant for either Newark and surrounding stations or Camden and surrounding stations. At some sites, urban–nonurban temperature differences have been decreasing over time, as in the case of Camden–Moorestown. In this case, Moorestown appears to be experiencing warming caused by the development of suburban sprawl with near-by malls and parking lots. At other stations, urban–nonurban temperature differences are increasing, as in the cases of Camden–Glassboro and Camden–Indian Mills.

5.3. Climate trends and projections

In both Newark and Camden, mean temperatures have been warming over the past 50 years. Mean temperatures in Camden tend to be slightly higher than temperatures in Newark in the cooler months, but are similar in the summer months. Based on data collected at the six stations in and around Newark, mean annual temperature in the Newark area has been warming by 0.1 °C per decade and many of the hottest years occurred in the decade of the 1990s. This trend is similar to that observed for the New York Metropolitan Region as a whole (which includes Newark) in the MetroEast Coast Regional Assessment of Climate Variability and Change (Rosenzweig and Solecki, 2001). The mean temperature in and around Camden has been warming at an even greater rate (0.2 °C per decade) over the past five decades.

Extrapolation of trends apparent in the observed climate data were compared to GCM temperature projections (Fig. 6). While temperature projections for the three GCMs differ, all three project that greenhouse gas forcing will cause regional temperatures to increase over the current century. With the exception of the GISS greenhouse gas and sulfate aerosol scenario (GSGS) for Newark, rates of temperature rise for all model projections are higher than those of the current trends scenarios.

The GISS GCM GG and GS scenarios project small decreases in wind speed that range from less than 1% up to 1.5% depending on the scenario, and small increases in cloud cover (Table 3). Average annual wind speeds at Newark Airport under current conditions are lower than the current wind speeds simulated by the GISS model. The difference is less than 0.2 m/s, while projected increases are on the order of 0.1 m/s. In general, GISS GCM wind speed and cloud cover projections are not statistically significant; however, the results provide

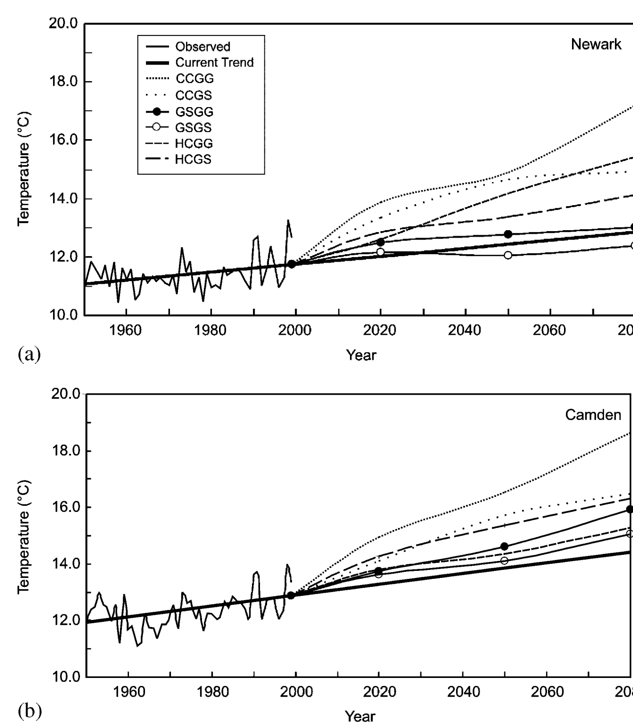

Fig. 6. Projected changes in annual mean temperature (a) Newark, (b) Camden.

some indication that wind speeds may decrease and cloud cover may increase toward the end of the century. Under both SRES scenarios, GISS GCM wind speeds are projected to decrease even more as the decades progress (approximately 5% by the 2080s) (Fig. 7). Changes in cloud cover in both the A2 and B2 scenarios were small.

Table 3
Windspeed and cloud cover modeled results for GSGG and GSGS in the Newark area

Decade	Wind speed (m/s)			Cloud cover (%)		
	Observed	GSGG	GSGS	Observed	GSGG	GSGS
1950	4.5	4.7	4.7	62	55	55
2000		4.7	4.7		55	56
2020		4.7	4.7		57	56
2050		4.6	4.7		57	57
2080		4.6	4.6		58	57

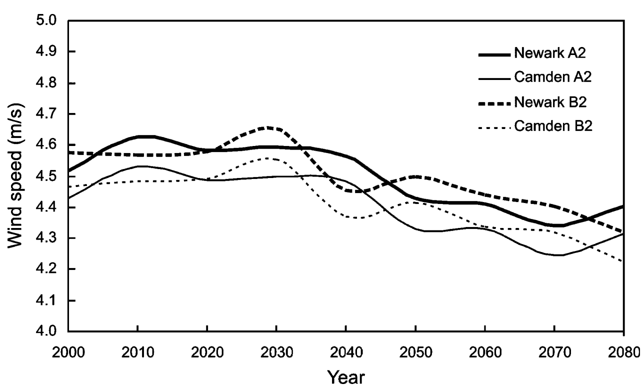

Fig. 7. Projected changes in mean temperature with SRES.

Further research in which coupled global/region-scale modeling systems are used is underway. This work involves coupling the GISS GCM to the MM5 mesoscale meteorological model. Such a system can be further integrated with air quality models (see Hogrefe et al., 2004).

5.4. Climate change, heat waves, and heat stress

Heat wave projections for the New York City Metropolitan area, which includes Newark, were developed using the MM5 mesoscale model (Grell et al., 1994; Lynn et al., 2003). The model projects that the number of days with maximum temperature greater than 32.2 °C in New York City will more than double by the 2020s and more than quadruple by the 2050s from 14 out of 92 summer days in the 1990s to 60 out of 92 summer days in the 2050s (Fig. 8). The GISS GCM projects that the frequency and duration of heat waves—periods of three consecutive days where maximum temperatures are above 34.4 °C and minimum temperatures are above 24.4 °C—will also dramatically increase. This could lead to a marked increase in summer mortality, even if people acclimatize to the increased warmth (Kalkstein and Greene, 1997).

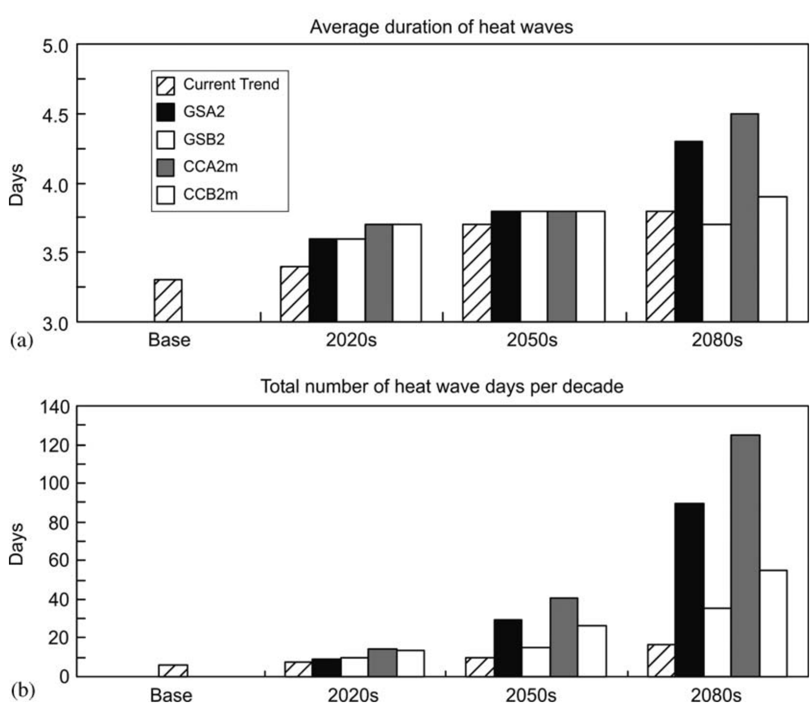

Fig. 8. Heat wave projections (a) average duration, (b) total number of heat wave days.

6. Discussion and conclusions

The UHI effect was detected in both the surface temperature record and the air temperature record for both Newark and Camden. Both extrapolation of current trends and GCM scenarios project that temperatures will continue to warm in the current century as they have been doing over the past half-century.

The strong relationship between wind speed and UHI intensity as well as that between cloud cover and UHI intensity in the region imply that changes in the magnitude of the UHI effect over the current century will depend at least in part on how cloud cover and wind speed change. An initial analysis of global climate change scenarios shows that wind speed may decline, while cloud cover may increase. These generally small countervailing tendencies suggest that urban–nonurban temperature differences may be maintained under climate change. Also, higher temperatures in paved urban areas may indirectly create a positive feedback by generating greater evaporative demand. This may further augment the UHI effect between urban and nonurban settings in the future.

Overall warmer conditions throughout the year may extend the spatial and temporal dimensions of the urban–suburban heat complex. The incidence of heat-related morbidity and mortality are likely to increase with interactions between the increased frequency and duration of heat waves and the UHI effect. Camden and Newark will likely be subjected to higher temperatures and areas experiencing UHI-like conditions and temperature extremes will expand. The area over which unhealthful concentrations of pollutants are experienced may increase as temperatures in dense suburban areas surrounding the city increase.

Though the magnitude of urban–suburban differences may not increase, the population affected by severe pollution episodes may increase as UHI-like conditions become more frequent in outlying suburban locations, presenting additional challenges for policy-makers. Warming temperatures may interact with the already low wind speeds that are characteristic of the Newark metropolitan area, increasing the potential for pollutants to become concentrated, especially in the summer time. Continued development to accommodate the growing population in New Jersey (a growth from the current estimate of 8.4–9.4 million people is expected by 2020) may also exacerbate these problems, if such development occurs as sprawl. Thus, climate change and its effects on the UHI are important components of planning for regional land use and hazard preparedness.

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